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We demonstrate the use of optically generated geometric phases to modify the phase of one of the spin states of an electron confined in an InAs quantum dot, effectively executing a spin phase gate.

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ABSTRACT

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REPORT DOCUMENTATION PAGE (SF298)
(Continuation Sheet)

Continuation for Block 13

ARO Report Number 55014.9-PH-QC
A Spin Phase Gate Basedon Optically Generate ...

Block 13: Supplementary Note

A Spin Phase Gate Based on Optically Generated Geometric Phases in a Self-Assembled Quantum Dot

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Abstract: We demonstrate the use of optically generated geometric phases to modify the phase of one of the spin states of an electron confined in an InAs quantum dot, effectively executing a spin phase gate.

OCIS codes: (270.1670)Coherent Optical Effects; (300.6470)Semiconductors Spectroscopy

For quantum computing implementations utilizing the spins of individual carriers in quantum dots (QDs) as quantum bits (qubits) [1, 2], spin control is a fundamental necessity. Optical control of these spins provides the prospect of ultrafast qubit operations with currently available laser technology [3, 4]. Recent experimental demonstrations have successfully shown the fast optical rotation of QD confined spins about the optical axis [5, 6, 7], though optically driven rotations about an orthogonal axis—which would enable all-optical qubit manipulations—have yet to be realized. Here, we present such a rotation by demonstrating a spin phase gate based on geometric phases [8] generated by a narrow-bandwidth continuous wave (CW) optical field. These acquired geometric phases may be observed by performing time-resolved studies of the precession of the electron spin about an external DC magnetic field applied perpendicular to the QD growth axis and manifest as phase shifts in the spin quantum beat signal.

Fig. 1(a) gives the energy level diagram for the electron spin states and the two lowest lying trion (negatively charged exciton) states for a magnetic field oriented along $\hat{z}$. At operating temperatures of ~ 5 K, the electron spin states are mixed and are thus first prepared in a pure state by driving the $|z+\rangle$ to $|t_z+\rangle$ transition with a V-polarized CW optical field, thereby optically pumping $|z+\rangle$ population to the $|z-\rangle$ state within a few nanoseconds [9]. Subsequent excitation with a red-detuned circularly polarized pulse 2 ps in width serves to rotate the spin about the optical axis $\hat{x}$ while generating negligible trion population [6]. For a rotation angle of $\pi/2$, the electron spin vector is rotated into the $\hat{x}$-$\hat{y}$ plane and begins to precess about $\hat{z}$ at a rate determined by the electron Zeeman splitting Δ_e.

Since the CW field used to initialize the spin is left on, it drives Rabi oscillations between the $|z+\rangle$ and $|t_z+\rangle$ states while the electron spin precesses and is re-initialized. For CW Rabi frequencies that are much greater than the trion relaxation rate yet sufficiently small so as not to drive the $|z-\rangle$ to $|t_z-\rangle$ transition, each complete Rabi oscillation may be considered a cyclic quantum evolution wherein $|z+\rangle$ acquires a geometric phase $\beta = \pi(1 - \delta/\Omega_g)$ where δ is the CW field detuning and $\Omega_g = \sqrt{\Omega^2 + \delta^2}$ is the generalized Rabi frequency for standard Rabi frequency Ω. $|z-\rangle$, on the other hand, does not acquire any phase since the $|z-\rangle$ to $|t_z-\rangle$ transition is not driven. As such, each optically imparted geometric phase acts as a spin phase gate. Further, since the spin is first prepared in a coherent superposition of $|z+\rangle$ and $|z-\rangle$ states, each spin phase gate operation results in the effective rotation of the spin about the $\hat{z}$ axis by an angle β. This rotation angle is in addition to the time-dependent rotation angle about $\hat{z}$ due to spin precession.

To observe the effect of the geometric phases, we measure the time-averaged absorption of the CW initialization field in experiments utilizing two time-delayed, red-detuned circularly polarized optical pulses. This technique effectively probes the $|z+\rangle$ population immediately after the second pulse. Figs. 1(b) and (c) plot

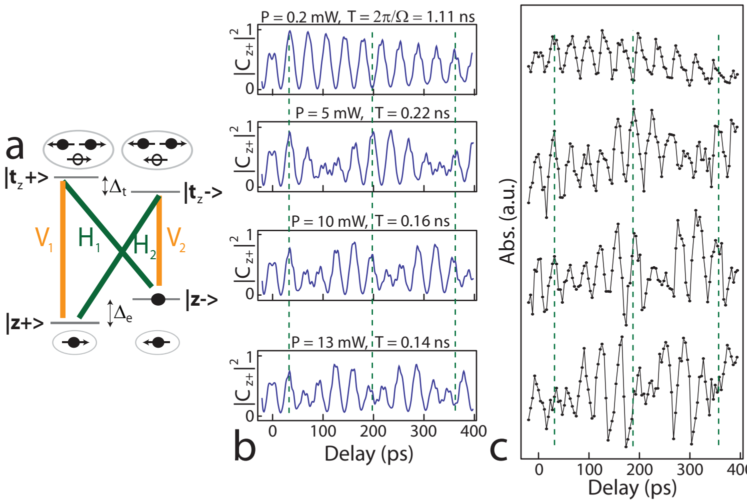

Fig. 1. (a) Energy level diagram for a negatively charged InAs QD with a DC magnetic field along $\hat{z}$. (b) Theoretically calculated $|z+\rangle$ populations after the second optical pulse as a function of pulse delay for different CW field powers and (c) the corresponding time-averaged CW absorption measurements.

the theoretical calculations of $|z+\rangle$ after the second pulse and the corresponding absorption measurements as a function of pulse delay for different CW powers. As a result of the CW-driven trion Rabi oscillations, the spin quantum beat signal is modulated by an oscillatory envelope of frequency Ω_g. In addition, the imparted geometric phases may be seen by comparing the absorption signal traces at the delays indicated by the green dashed lines. Since the CW field is resonant with the $|z+\rangle$ to $|t_z+\rangle$ transition, $\beta = \pi$ ($\Omega_g = \Omega$) and each complete Rabi oscillation leads to a π phase shift in the electron spin quantum beat signal. Thus, at ~ 200 ps, the 5 mW and 10 mW quantum beat signals, which have each undergone roughly a single trion Rabi oscillation, are π out of phase with the .2 mW signal, which has not, though the quantum beat signals for all powers are initially in phase. At ~ 350 ps, the 5 mW and 10 mW quantum beat signals, each having undergone roughly two trion Rabi oscillations, are once again in phase with the .2 mW quantum beat signal. We note that the 13 mW quantum beat signal at both ~ 200 ps and ~ 350 ps is nearly at a point where the $|z+\rangle$ population is depleted. Near such points, the quantum beat phase changes rapidly as it undergoes a Guoy-like shift, making it difficult to compare with those of the other quantum beat signals. These results are the first experimental demonstration of an optically driven spin rotation about an axis orthogonal to the optical axis and provide a proof of principle for the pulse-driven rotations proposed in Ref. [4].

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